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Interaction of earthworm burrows and cracks in a clayey, subsurface-drained, soil

Martin J. Shipitalo[a,*], Visa Nuutinen[b], Kevin R. Butt[c]

[a] USDA-ARS, North Appalachian Experimental Watershed, P.O. Box 488, Coshocton, OH 43812-0488, USA
[b] MTT Agrifood Research Finland, Soils and Environment, FI-31600 Jokioinen, Finland
[c] Department of Environmental Management, University of Central Lancashire, PR1 2HE Preston, UK

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Abstract

Installation of subsurface tile lines in poorly drained soils is a beneficial management practice that enhances crop productivity. In some instances, however, they can contribute to offsite losses of agricultural chemicals and sediment in drain flow. Movement of these materials through soil macropores (earthworm burrows and cracks) has been shown to contribute to this phenomenon. In order to determine if there was any interaction between these two types of macropores and subsurface drains we investigated water movement in a sandy clay field in southwest Finland that had 1 m-deep tile drains installed in the 1950s. Previous studies at this site suggested that cracks were important in terms of water movement and that *Lumbricus terrestris* L. populations were greater, and their burrows deeper, above the drains than in the area between drains. Mean infiltration rate for soil above the drains was twice that of the mid-drain position and the infiltration rates were positively correlated to *L. terrestris* numbers and biomass. Infiltration rates in individual *L. terrestris* burrows, measured with the plow layer removed to reduce the influence of cracks, ranged from 6 to 1043 ml min^{-1} (average 358 ml min^{-1}) and did not appear to be related to the position of the burrows relative to the buried tile. Consistently higher infiltration rates (average 1080 ml min^{-1}) were noted when measurements were made with the plow layer intact. Dye poured into the cracks adjacent to these burrows indicated water movement to the base of the plow layer, which acted as a hydraulic barrier, followed by lateral movement until open earthworm burrows were encountered. Water movement to the depth of the tile was exclusively in *L. terrestris* burrows with 106 dyed burrows m^{-2} observed 10 cm above the tile. These observations indicate that entry of water into this soil is probably dominated by cracks when it is dry enough for their formation, yet rapid movement of materials entrained by this flow to the subsurface drains depends on connection of the cracks to earthworm burrows.
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Keywords: Infiltration; Preferential flow; Macropores; Sediment loss; Subsurface drainage; Water quality

1. Introduction

Subsurface drainage improves soil productivity by removing excess water and is widely used in many agricultural regions of the world. While drainage has positive effects in terms of crop growth and soil conservation, it can also contribute to offsite losses of agrochemicals and sediment (Kladivko et al., 2001). In Finland, where many of the soils used for crop production are clayey soils of marine lacustrine origin, subsurface drainage is used on 54% of the agricultural land (Anonymous, 2002) and 80% of the clay

* Corresponding author. Tel.: +1-740-545-6349;
fax: +1-740-545-5125.
E-mail address: martin@coshocton.ars.usda.gov (M.J. Shipitalo).

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soils (Turtola and Paajanen, 1995). Recent studies on these soils have shown that annual losses of water, particulate phosphorus, and sediment from sub-drains are of similar magnitude to those measured in surface runoff, thus are an important contributor to surface water quality concerns (Paasonen-Kivekäs and Virtanen, 1998; Turtola and Paajanen, 1995). Cesium isotope analysis further indicates that much of the sediment in the drains originates from the Ap horizon (Uusitalo et al., 2001). This suggests that the sediment and other contaminants originated in surficial soil horizons and must have been transmitted through the soil profile to the drains via macropore flow paths (i.e., biopores and cracks). In fact, macropores were recognized as having a major impact on the quality of drainage water more than a century ago (Lawes et al., 1882), although this observation was largely ignored until the 1980s (Beven and Germann, 1982).

Although the critical times for sub-drain function in clayey, Finnish soils are in the spring and fall when the soils are wet, cracks usually form during the summer when the soils are dry and are believed to be important pathways of water movement (Aura, 1995; Yli-Halla and Mokma, 2001). These cracks tend to close when the soil wets up and infiltration rates have been observed to drop dramatically (Aura, 1995). Studies in other parts of the world also suggest that cracks can be important contributors to preferential flow and movement of contaminants to drain lines. For example, in Canada, Gaynor and Findlay (1995) also noted that sediment and phosphorus loss were greater in tile drains than in surface runoff, which they attributed to preferential flow in cracks. In Norway, Øygarden et al. (1997) noted that cracks extending into the backfill surrounding drain pipes contributed to the loss of soil particles from the plow layer in the drainage system.

Earthworm-formed macropores can also have a major influence on water and chemical movement in soil (McCoy et al., 1994; Shipitalo et al., 2000). Unlike cracks, however, earthworm burrows can continue to function as preferential flow paths under wet soil conditions (Friend and Chan, 1995). Moreover, vertical burrows formed by anecic earthworms are less likely to be closed by vehicle-induced compaction than other types of soil macropores (Alakukku et al., 2002). Additionally, recent studies in Finland indicated that the populations and biomass of the anecic earthworm *Lumbricus terrestris* L. were greater (Nuutinen et al., 2001), and their burrows deeper (Nuutinen and Butt, 2003), above the drains than in the area between drains. Similarly, in Canada, higher earthworm numbers and biomass were noted in a tile-drained field than in an undrained field (Carter et al., 1982); and in the former Czechoslovakia earthworm burrows were more abundant in the humus-rich, tile backfill material than in the surrounding soil (Urbánek and Doleñal, 1992). Studies of *L. terrestris* burrows in a sub-drained field in the United States indicated that infiltration rates declined rapidly with distance from the drain line, suggesting that those burrows in the immediate vicinity of the drain may be involved in contaminant transport offsite via the buried drains (Shipitalo and Gibbs, 2000).

Thus, studies in Finland and elsewhere in the world clearly indicate that earthworm burrows and cracks can be important pathways for preferential flow. This can be of particular concern in sub-drained fields where these macropores may transmit water and contaminants directly to drains that lead to surface waters. Greater earthworm populations, deeper burrows, and higher infiltration rates in burrows in the vicinity of drain lines than in the surrounding soil may accentuate the effects of earthworm-formed macropores on sub-drain function. The potential interactions between cracks, earthworm burrows, and sub-drains, however, have yet to be investigated. Therefore, our objective was to investigate the pathways of water movement in a sub-drained, cracked, Finnish soil with a resident *L. terrestris* population.

2. Materials and methods

An 8 ha field with a sandy clay plow layer (40–46% clay) near Jokioinen, southwestern Finland was selected for study. A few centimeters of sand were used to backfill around the clay tiles in this field when the drains lines were installed (ca. 1950) at a depth of 1 m and a spacing of 16 m. Although illite is the dominant clay mineral in these lacustrine soils, extensive cracking occurs when they dry due to their high clay content. The soils classify as Vertic or Typic Cryaquepts according to Soil Taxonomy and Vertic Cambisols in the FAO–UNESCO system (Yli-Halla and Mokma, 2001).

Table 1
Average monthly temperature and rainfall at Jokioinen (1961–1990) and for 2002

Month	Temperature (°C)		Precipitation (mm)	
	2002	1961–1990	2002	1961–1990
June	15.4	14.3	95	47
July	18.2	15.8	66	80
August	17.9	14.2	13	83

Field experiments were conducted in August 2002 when the soil had an extensive network of 1–1.5 cm wide cracks visible at the soil surface. Summer 2002 was unusually warm in Jokioinen and August was exceptionally dry, which contributed to crack formation (Table 1). The field was in grass-cereal rotation and was moldboard plowed the previous autumn prior to planting of spring barley (*Hordeum vulgare* L.). A metal probe was used to determine the position of two drain lines in the field. A 2 m $\times$ 2 m section of the plow layer soil was removed using shovels to a depth of approximately 25 cm above one of the drain lines. Afterwards, the exposed surface was scraped and vacuumed to reveal the openings of earthworm burrows $\geq$5 mm in diameter. The distance of the openings from the drain line was recorded and infiltration rates in the individual burrows were measured using the procedures and equipment developed by Shipitalo and Butt (1999). This consisted of inserting a funnel with a flexible spout into each burrow opening. A 6.8 l capacity Mariotte-type infiltrometer was then used to maintain a constant head of water in each funnel and the rate of water entry into individual burrows was measured for 30 minutes. The water level in the infiltrometer was recorded every minute for the first 2 min then every 2 min thereafter. If the intake of a burrow exceeded the capacity of the infiltrometer during the 30-min period additional infiltrometers were used to complete the measurement. Infiltration rates were calculated for each burrow for each time interval beginning with the 2-min reading since the 1-min reading includes the amount of water required to initially fill the burrow and intake funnel.

A dilute solution of formalin was used to expel earthworms from a 2 m $\times$ 2 m area above the other drain line, and we noted the position of the burrows from which they emerged. Infiltration rates were once again measured for each burrow. In this instance, however, the plow layer was left intact and undisturbed. Afterwards, a solution of methylene blue dye was poured directly into the cracks within the experimental area. Plastic replicas of the burrows were then made by pouring fiberglass resin, dyed white with TiO_2, into the opening of each burrow.

After allowing time for the resin to cure, trenches were mechanically opened adjacent to the plot area and parallel to the drain line. Hand tools were then used to remove the soil in the vertical faces so that the pattern of dye and resin movement could be observed. Excavation was continued until the buried tile was encountered, at which time a horizontal face approximately 40 cm wide by 65 cm long was exposed 10 cm above the buried drain line. The number of stained burrows observed at this depth was then counted.

3. Results and discussion

3.1. *Infiltration rates and capacity*

Previous research at this site indicated that *L. terrestris* populations above the buried drains were twice those measured in the mid-drain positions (4.5 individuals m^{-2} versus 2.1 individuals m^{-2}) while biomass was five times higher due to a greater proportion of adults in the population (Nuutinen et al., 2001). Additionally, the burrows above the drains were deeper (1.00 m versus 0.83 m) than in the mid-drain areas (Nuutinen and Butt, 2003). We hypothesized that the greater number and depth of burrows in the vicinity of the drain would contribute to higher infiltration in the bulk soil than in the soil between drain lines, because of greater contribution of the burrows to the infiltration rate of the bulk soil. Measurements of bulk soil infiltration conducted 30 September to 9 October 1998 during the grass phase of the rotation support this hypothesis, as the mean infiltration rate was twice as high above the tile than at the midpoint between the tile lines (Table 2). Further analysis of this data revealed that infiltration rate was positively correlated to *L. terrestris* numbers ($r = 0.31$, $P = 0.006$) and biomass ($r = 0.33$, $P = 0.004$) measured 23–28 September 1998 (Nuutinen et al., 2001), approximately 2 m from the sites of the infiltration measurements.

Table 2
Infiltration of the bulk soil above and between tile lines as measured using 0.5 m^2 single ring infiltrometers (S.E., standard error of the mean)

	Infiltration rate ($mm\,h^{-1}$)					
	N	Mean	S.E.	Median	Minimum	Maximum
Above tiles	40	172.1	18.8	146.6	7.5	486.9
Between tiles	38	79.7	10.8	55.5	2.8	236.9

We further hypothesized that close proximity of some burrows to the drain might also increase infiltration due to rapid movement of water directly from the burrows to the drain. To test this hypothesis, infiltration rate of earthworm burrows was measured following removal of the plow layer in order to reduce the influence of cracks on the infiltration measurements and to determine if there was a relationship between infiltration rate and proximity of the burrows to the buried tile. A total of 13 burrows with diameters of ≥5 mm suitable for infiltration measurements were identified in the 4 m^2 area with the plow layer removed. This density of burrows (i.e., 3.25 m^{-2}) falls within the range of *L. terrestris* populations noted by Nuutinen et al. (2001) and it is likely that all were formed by this species. The two most common earthworms in arable Finnish soils, and the only two species noted in a nearby crop field, are *L. terrestris* and *Aporrectodea caliginosa* Sav. Unlike *L. terrestris* burrows, those formed by the soil-dwelling, endogeic, *A. caliginosa* were most frequently found in the upper portions of the soil profile and were usually <5 mm in diameter (Pitkänen and Nuutinen, 1997).

The measurements indicated that the average infiltration rate for the burrows declined by 32% with time, from 472 $ml\,min^{-1}$ at 2 min to 323 $ml\,min^{-1}$ at the final interval. Regression analysis for individual burrows indicated that infiltration rate declined significantly ($P \leq 0.05$) with time for 7 of the 13 burrows. The 30-minute average infiltration rates for the burrows were highly variable, ranging from 6 to 1043 $ml\,min^{-1}$, and did not appear to be related to the position of the burrows relative to the buried tile (Fig. 1). The average rate for all burrows (358 $ml\,min^{-1}$) and the individual rates for nearly half the burrows were greater than the highest rate (353 $ml\,min^{-1}$) reported by Shipitalo and Gibbs (2000) for *L. terrestris* burrows in a heavy-textured, sub-drained, field in the US. In that study, however, high infiltration rates were associated with close proximity of burrows to the buried drain (ca. 0.5 m). Although we removed the plow layer to minimize the influence of open cracks on the burrow infiltration measurements, in some instances wetting of crack planes visible at the prepared soil surface was noted for those burrows with high infiltration rates. Thus, we were unable to determine if high infiltration rates were attributable to proximity of the burrows to the drain, to cracks, or to a combination of these two factors. Regardless, the data indicated that even at the average infiltration rate (358 $ml\,min^{-1}$) and burrow density (3.25 burrows m^{-2}) the burrows could potentially contribute 70 $mm\,h^{-1}$ to the infiltration rate of the bulk soil below the plow layer. This estimate corresponds closely to the mean bulk soil infiltration rate (79.7 $mm\,h^{-1}$) measured with single ring infiltrometers between tile lines (Table 2).

Application of formalin to the 2 m × 2 m area with undisturbed topsoil resulted in the collection of a total of seven earthworms, all *L. terrestris*. The number of *L. terrestris* obtained was less than expected, based on the population assessments made by Nuutinen et al.

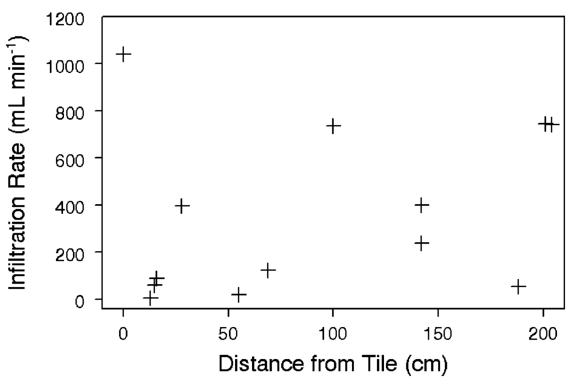

Fig. 1. Average infiltration in earthworm burrows, measured with the Ap horizon removed, as a function of distance from the tile sub-drain.

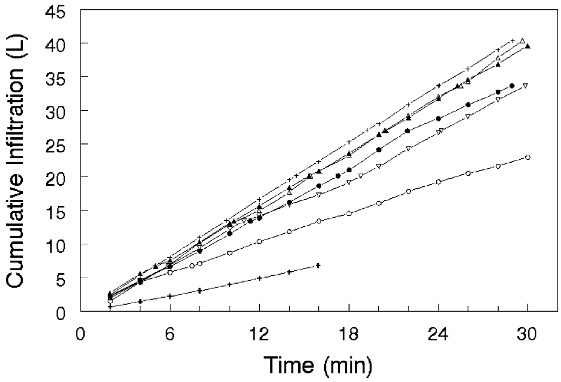

Fig. 2. Cumulative infiltration in seven, individual *L. terrestris* burrows measured at the soil surface.

(2001), probably due to poor extraction efficiency related to the dry soil conditions. Following collection of the earthworms, infiltration measurements were made for each burrow. Infiltration rates for these burrows were uniformly high during the 30-min measurement period and approximated the maximum delivery rate of the infiltrometer-intake funnel system (Fig. 2). In one instance, however, the soil surrounding one of the burrows did not support the intake funnel upon wetting and eventually plugged the burrow resulting in the termination of measurements after 16 min (Fig. 2). Unlike the measurements with the topsoil removed, there was essentially no change in infiltration rate with time as indicated by only slight variation between the 2 min (1057 ml min^{-1}), final (1084 ml min^{-1}), and average (1080 ml min^{-1}) values. Up to 40 l of water was added to individual burrows during the 30-min period, suggesting a tremendous potential contribution of the earthworm burrows to the infiltration rate of the bulk soil at the soil surface. Once again there was no apparent relationship between infiltration rate and the proximity of the burrows to the buried drain.

3.2. *Patterns of water movement*

Following completion of the infiltration measurements dye was poured into the cracks at a rate sufficient to avoid filling the cracks and distributing dye onto the soil surface. Thus, the only route of entry for the dye into the soil was via the cracks. Afterwards, several hundred milliliters of resin were added to each burrow. This volume of resin was insufficient to completely fill the burrows in all cases, despite the fact that maximum reported volumes of *L. terrestris* burrows measured in this manner for three different soil types ranged from 48 to 65 cm^3 (Shipitalo and Butt, 1999; Shipitalo and Gibbs, 2000).

Excavation revealed fairly uniform staining of the soil along the walls of the cracks to the depth of the plow layer with little penetration into the surrounding soil (Fig. 3). Typically the cracks did not extend deeper than the bottom of the plow layer, but some were observed to a depth of 30–35 cm. Upon reaching the base of the plow layer the dyed water moved laterally until encountering open earthworm burrows. The dyed water then moved to the base of the earthworm burrows and, once again, little penetration into the surrounding soil matrix was noted (Fig. 3). In most instances no connection of the stained burrows to the soil surface was noted, suggesting that their continuity above the plow layer had been disrupted by tillage. Thus, the base of the plow layer acted as temporary hydraulic barrier, probably due to compaction and sealing of the structural porosity caused by years of tillage. This promoted ponding of water above the plow layer and lateral movement until open macropores were encountered. Thomas and Phillips (1979) postulated that such a phenomenon could occur and Pitkänen and Nuutinen (1998) observed entry of water into earthworm burrows at the topsoil–subsoil interface in soil cores subjected to simulated rain in a laboratory study. The fiberglass resin added to the earthworm burrows after the infiltration measurements, and after dye addition to the cracks, did not completely fill any of the burrows. In all cases lateral spreading of the resin was noted at the topsoil–subsoil interface (Fig. 3) and in a number of instances resin entry into adjacent cracks was observed. This accounted for the inability to fill the burrows with resin and indicated that high infiltration rates measured for all these burrows were at least partially attributable to movement of water into cracks and lateral movement at the bottom of the plow layer.

Observation of dye patterns at a depth of 90 cm (10 cm above the tile) revealed that stained earthworm burrows were far more numerous than the number of burrows observed higher in the profile and the earthworm populations measured by Nuutinen et al. (2001). A total of 26 burrows (110 burrows m^{-2}) were observed above the tile line and all but one was stained with dye (Fig. 4). This suggests that the burrows were

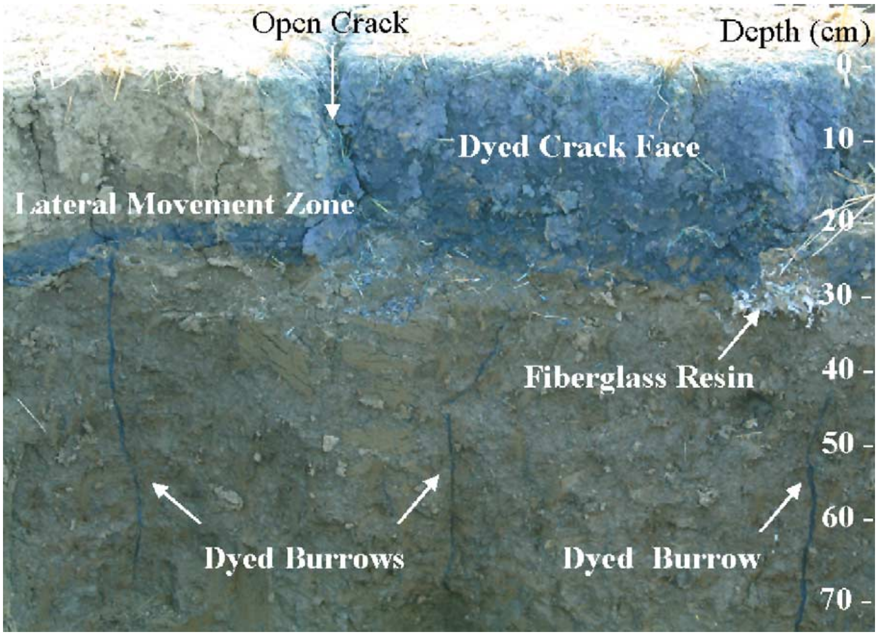

Fig. 3. Distribution of methylene blue dye added to cracks at the soil surface. Note lateral movement at the plow layer—subsoil interface and deep movement in earthworm burrows.

constructed some time in the past and abandoned, but were disrupted higher in the profile due to tillage or other forms of soil disturbance such as compaction, freeze–thaw, and shrink–swell. Other researchers have noted that open earthworm burrows are more numerous with depth in the profile for the reasons indicated above (Daniel et al., 1997; Ligthart, 1997). In our study, however, the dye movement suggests that these

Fig. 4. Distribution of methylene blue dye added to cracks at the soil surface as observed in a horizontal surface at a depth of 90 cm, 10 cm above the buried tile sub-drain. Dyed areas outlined in white.

Fig. 5. These *L. terrestris* burrows, filled in situ with fiberglass resin, where vertical in the upper portion of the soil profile, but turned into the sandy backfill surrounding the tile at 1 m depth and ended on the tile surface.

truncated burrows can remain hydrologically active due to their connection to the soil surface via cracks and the plow layer-subsoil interface. The number of burrows we observed was similar in magnitude to the 175 *L. terrestris* burrows m^{-2} measured in the subsoil of this field in 2001 (Nuutinen and Butt, unpublished observation) and to the 180 burrows m^{-2} noted by Pitkänen and Nuutinen (1997) at a depth of 80 cm in a nearby field. Dye movement to the depth of the tile was exclusively in earthworm burrows as there was no evidence of dye movement to this depth in cracks.

Although no complete resin-filled burrows were obtained, several partially cast burrows were noted within the sand layer surrounding the buried tile. Nuutinen and Butt (2003) also observed resin-filled burrows within the sand layer and ending at the tile surface in this field (Fig. 5). They hypothesized that formation of deeper and more numerous burrows by *L. terrestris* above the tile line might be promoted by better aeration due to a lower water table or to the lower clay content in the soil used as backfill than in the surrounding soil. Earthworms are generally absent or rare in coarse-textured soils due the abrasive nature of the sand and the susceptibility of such soils to drought while in clayey soils in humid regions oxygen deficits can limit their populations (Lee, 1985). In this instance, *L. terrestris* appeared to preferentially burrow towards the tile because of better aeration in this zone, despite its surrounding envelope of coarse-textured sand.

3.3. Management implications

Our measurements indicated that earthworm burrows in this soil exhibited high infiltration rates ($\sim$1000 ml min^{-1}) when the soil surface was left intact. It is unlikely that this amount of water would be available to enter burrows at the soil surface under natural conditions, unless there was surface ponding. When monitored in the field under natural rainfall, Edwards et al. (1989) noted that the amount of water transmitted by *L. terrestris* burrows increased with storm intensity to a maximum of 10% of rainfall, which was equivalent to the amount of rainfall on an area about 13 times the size of the burrow openings. When monitored on a yearly basis at seven fields subject under a variety of production practices the amount of rainfall transmitted by *L. terrestris* burrows averaged <5% of total rainfall (Shipitalo et al., 1994). Our study suggests, however, there was considerable interaction between the network of cracks and the earthworm burrows that would affect the supply of water available to enter earthworm burrows below the plow layer.

When the soil is dry enough for the cracks to form, the majority of the rainwater not sorbed by the soil matrix is likely to enter the soil via the cracks, rather than directly enter the earthworm burrows at the soil surface. The dye poured into the cracks indicated that this water did not penetrate much beyond the plow layer, but moved horizontally along this interface until earthworm burrows were encountered. This could greatly increase the supply of water available to infiltrate into the burrows, beyond that available at the soil surface. The burrows need not be currently inhabited to transmit water as the dye indicated that the number of hydrologically active burrows was much larger than the earthworm population. Unless the burrows are closely associated with the drain tile, however, it is doubtful that the high infiltration rates would be maintained for long given the slow permeability of the subsoil. In this soil earthworm burrows appeared to be the only pathway that could rapidly conduct water to the sub-drain as there was no evidence of cracks or other macropores extending to this depth. Even though the soil was quite dry at the surface ($\theta = 0.21$ kg kg^{-1} at 0–10 cm) at the time the experiments were conducted, it remained fairly wet at the depth of the sub-drain ($\theta = 0.40$ kg kg^{-1} at 90–100 cm). Thus, it is unlikely this soil would dry enough in most years for cracks to reach the sub-drain and there was no morphological evidence that cracks had ever occurred at this depth, although cracks up to 70 cm deep have been observed in soils elsewhere in the Jokioinen region (Alakukku, unpublished observation).

When the surface soil is wet, and cracks are smaller and less numerous, direct entry of water into the burrows should become relatively more prevalent than entry via the crack network. Similarly, matrix flow should be more prevalent than under dry soil conditions (Shipitalo et al., 2000). Nevertheless, water movement through the soil matrix porosity should be impeded at the topsoil–subsoil interface due to the low hydraulic conductivity of this zone. The resulting saturated soil conditions at this interface should again foster lateral flow and entry of water into the earthworm burrows at this depth via this mechanism.

Rapid movement of water to the drains in earthworm burrows could contribute to the movement of sediment originating in the Ap horizon to the sub-drains as observed by Uusitalo et al. (2001) and raises concern regarding direct transference of other materials such as nutrients, pesticides, manure, and pathogens to the drains. In fact, Shipitalo and Gibbs (2000) noted that *L. terrestris* burrows can contribute to rapid movement of liquid animal wastes to sub-drains. In that instance, however, connection to the sub-drain was limited to burrows that occurred 0.5 m either side of the drain. Thus, avoiding application of wastes in this region or tilling to disrupt the burrows above the sub-drain before waste application were suggested as management practices that could alleviate this concern. In the current case, however, these remedies would probably not be successful as it was evident that water that enters the cracks or soil matrix can move substantial distances (i.e., several meters) laterally before encountering burrows and moving to the sub-drain. Other researchers have also noted that materials applied at relatively large distances from sub-drains can be rapidly transmitted to the drains. In a review of the literature, Kladivko et al. (2001) maintain that the results of studies in which conservative and reactive tracers applied in strips offset 1.5–2 m from sub-drains exhibit rapid, simultaneous, breakthrough, despite wide variation in the sorption coefficients of the tracers, indicate that preferential flow was the cause and that it is not related to soil disturbance caused by drain installation.

Management practices that disrupt the linkage of cracks to earthworm burrows through the plow pan might help reduce movement of sediment and other contaminants to sub-drains. This might include the use of conservation tillage practices as an alternative to moldboard plowing in order to inhibit formation of a hydraulic barrier at topsoil–subsoil interface. No-till practices have been shown to reduce sediment losses in drains in clayey Norwegian soils prone to cracking (Øygarden et al., 1997). Use of lightweight tractors might further reduce compaction and prevent reformation of plow pans (Alakukku et al., 2002).

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